OPTICAL REVIEW Vol. 5, No. 5 (1998) 285-290

# Improvement of Laser-Beam Irradiation-Intensity Distribution Using Multi Lens Array and Edge-Shaped Plates

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(Received November 17, 1997; Accepted May 21, 1998)

A new concept for improving the laser intensity distribution on an inertial confinement fusion target using a phase-controlled multi lens array has been proposed. Circular and hexagonal element lens apertures have been examined, and the circular aperture which eliminated azimuthally asymmetric intensity distribution was chosen. The diffraction fringe of the elementary lens was mitigated in a one-dimensional lens array using edge-shaped plates of a super-Gaussian phase profile. Uniform beam profiles were obtained using a one-dimensional array with 7 spherical lenses and a two-dimensional array with 37 lenses. An approximately flat-top intensity distribution was realized with the lens array with 37 lenses.

**Key words :** envelope profile control, illumination uniformity, multi lens array, diffraction fringe, edge-shaped plate

## 1. Introduction

Uniform laser irradiation is one of the key issues in laser fusion research. Envelope profile control is essential in reducing the lower-mode of the irradiation nonuniformity. The laser illumination uniformity is determined by inherent parameters of the laser system, such as the number of beams and the geometrical arrangement of the laser illumination, and by controllable parameters, such as the irradiation condition (for example, the target offset from the focal point), spatial intensity distribution of laser light and power imbalance between individual beams. To reduce the intensity modulation of the irradiation beam, several beam smoothing technologies, such as the use of a random-phase plate (RPP)[1] induced spatial coherence (ISI)[2] optical fiber smoothing (OFS)[3] beam smoothing by spectral dispersion (SSD)[4] and amplified spontaneous emission (ASE)[5] have been proposed. In RPP approaches, spatially multimode light is used to decrease the spatial coherence, and a very large number of small beamlets (1-2 mm) overlap the same irradiation surface of the target. Therefore, the beam pattern of RPP includes spatially short-wavelength modulations due to the interference of beamlets at large interference angles, and includes spatially long-wavelength modulations originating from the interference of neighboring beamlets. In other approaches, partially coherent light (PCL) is coupled with the RPP scheme. PCL consists of spatially and temporally multimode light of limited mode numbers. Therefore, PCL mitigates the interference fringes due to the intensity integration of the beam pattern throughout the duration of the laser pulse. However, the instantaneous beam pattern includes spatially short- and long-wavelength modulation due to RPP. The short-wavelength modulation is alleviated by the lateral thermal conduction (thermal smoothing) in the target plasma. However, the long-wavelength modulation is not alleviated by the thermal smoothing. In previous approaches, the elimination of spatially long-wavelength modulation and the control of the intensity distribution on the target were difficult. Use of a Kinoform phase plate (KPP)[6] was recently proposed to control the intensity distribution using the binary optical element consisting of 16 steps. Although a KPP can be designed to give the desired beam profile on the target, the most effective beam profile through a long-scale length target plasma is not known. The beam profile should be affected by the density profile of the plasma due to the phase change of the ray in the plasma.

In this paper, we describe a new concept for improving the laser intensity distribution using the circular-aperture multi lens array.[7] In Sect. 2, we explain the advantages and disadvantages of this spherical multi lens array. In Sect. 3, we describe the difference due to circular and hexagonal element lens apertures. A one-dimensional lens array with edge-shaped plates is described in Sect. 4 and, in Sect. 5, the effectiveness of the two-dimensional lens array is proved using an additional aberrator, with conclusions given in Sect. 6.

## 2. Fundamental Scheme of Spherical Multi Lens Array

The fundamental scheme of the spherical multi lens array (MLA) is shown in Fig. 1 as proposed by Deng *et al.*[8] A lens array consisting of small element lenses with the same focal length is used in front of the principal focusing lens. The lens array splits the incident beam into a large number of beamlets (30 to 100 beamlets). All beamlets overlap on the same region of the target surface. The intensity modulations of the incident beam are reduced by the overlap effect of each beamlet. An approximately flat-top intensity distribution can be obtained with a spherical MLA. The long-wavelength modulation is not produced by the interference because the interference angle of beamlets is large in the case of the MLA than in the case of RPP. The fringe separation of the lowest order is determined using,

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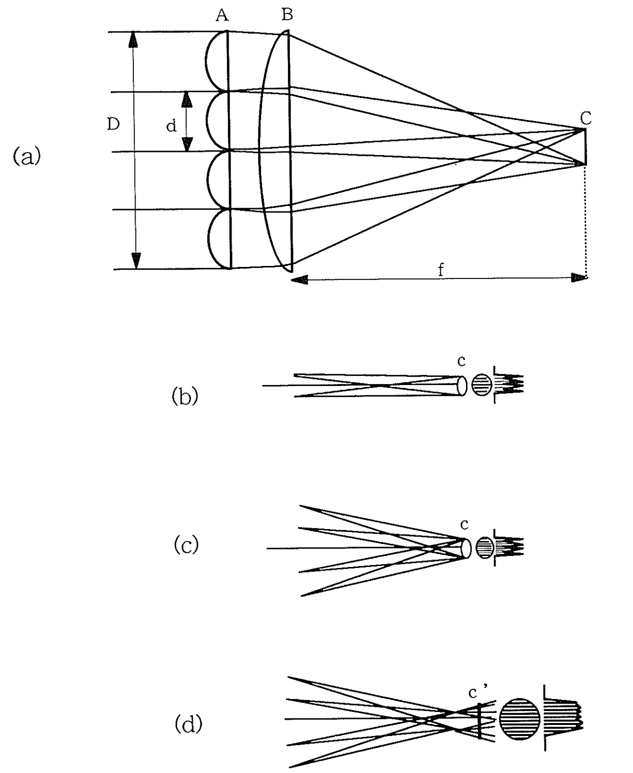


Fig. 1. Schematic drawing of multi-lens array: (a) whole beam system, where A, MLA; B, a main focusing lens; C, a focal plane; D, diameter of the main focusing lens; d, diameter of an element lens; f, focal length of the element lens, (b) interference of neighboring beamlets, (c) interference of 4 beams, (d) defocus from the focal plane.

$$a=\lambda/\sin(d/f)\,, \tag{1}$$

where $a$ is the fringe separation, $\lambda$ is the wavelength of the laser beam, $d$ is the size of the element lens, and $f$ is the focal length of the principal lens.

In the GEKKO XII glass laser system, the beam diameter is 350 mm, and the focal length of the principal lens is approximately 1 m. If the diameter of the element lens is 53 mm, the longest separation of the interference fringe is about 10 $\mu$m on the target. This means that the lowest mode number of spherical harmonics of the intensity modulation on the target is on the order of 100 at a target diameter of 500 $\mu$m. This fringe separation is fine enough for uniform illumination because thermal smoothing is effective in the target plasma.

Although the MLA scheme has the advantages mentioned above, the spherical MLA has two disadvantages. The first is intensity modulation due to diffraction by the element lens aperture. The diffraction fringe produces strong intensity modulation in the pattern of each beamlet. Defocusing of the target provides the mitigation of this diffraction pattern and the control of the intensity distribution in the beam profile. However, under the defocused condition, a second problem arises due to the influence of the original beam modulation at the edge of the irradiation pattern. The number of overlapping beams becomes very small at the edge, and the direct modulation remains in the incident beam.

## 3. Aperture Shape of Element Lens

Previous work on the multi lens array was conducted using an element lens with a hexagonal aperture,[8] however, this aperture caused azimuthal asymmetric intensity distribution in the beam pattern on the target. To compare the beam patterns of different element lens apertures, the patterns were measured using a TV camera at the geometrical beam spot size of 1 mm using He-Ne laser light. Each pattern was digitized and analyzed using an image processing device. The intensity distribution of the beam pattern of the hexagonal-aperture element lens at the focal point of the principal lens is shown in Fig. 2(a); azimuthal asymmetric spots due to the diffraction effect at the corner of the aperture are also indicated. To eliminate this asymmetric intensity distribution, we have selected the circular aperture, which generate symmetry beam pattern. The intensity distribution of the beam pattern of the circular aperture element lens is shown in Fig. 2(b), where a concentric-circle structure due to the diffraction fringe is visible. However, we have proposed a new concept to reduce the diffraction fringe using an edge-shaped plate.[9] This plate is a plane parallel glass plate having a continuously increasing curvature at the edge. A diffraction code to calculate the diffraction pattern from the light source which has an aspherical phase (or nonuniform intensity distribution) is required to evaluate the aspherical optical component. Unfortunately, the formula generally used in the diffraction calculation includes approximations such as Fresnel or Fraunhofer diffraction. The diffraction integration is very difficult to solve analytically when the distribution of light sources is aspherical. The conventional diffraction code is not accurate under an arbitrary continuous-phase condition such as when the edge-shaped plate is used in this work. The diffraction code used in this work, however, does not include such an approximation, and the complex amplitude of the irradiation is integrated directly. A very large number of point sources can be placed on the incident plane with a given amplitude and phase distribution. The distance between point sources should be narrower than the wavelength for tolerable calculation error. We expressed the surface shape of the optics using an aspherical function, for simplicity. The edge profile of the edge-shaped plate used in this case was a super-Gaussian function ($y(r)=\exp(-(r/w_0)^n)$, $w_0=20$ mm, $n=88$). The detail of the plate was given in the previous paper.[9]

To compare of the effects of the conventional soft aperture and the edge-shaped plate, the focusing efficiency of the soft aperture (absorber type, $w=25$, $n=10$–$40$) and the edge-shaped plate were calculated using our code for the focused beam diameter of 1 mm. The range of the order of the soft aperture ($n=10$–$40$) is chosen to give smooth profiles at the beam diameter of 1 mm. Energy losses at the 1 mm diameter target for the soft aperture and the edge-shaped plate (the edge profile of super Gaussian

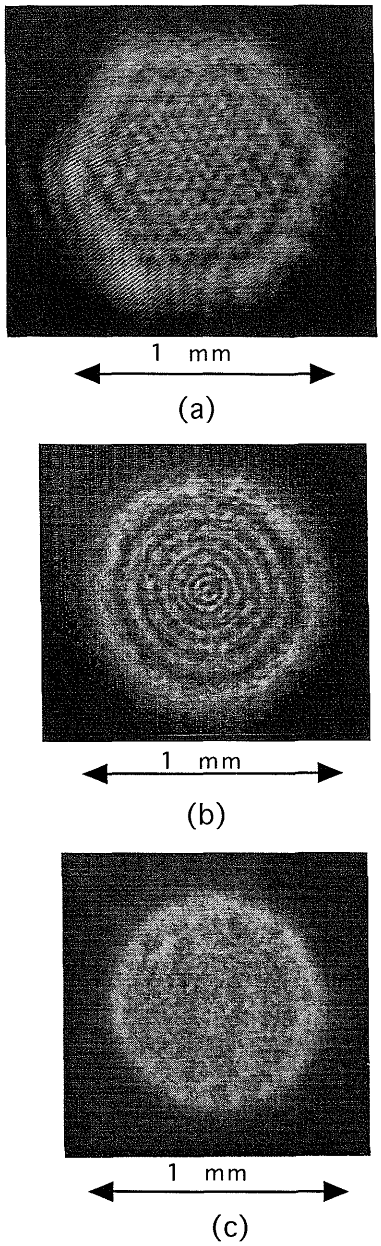


Fig. 2. Beam patterns of the hexagonal and circular aperture lenses: (a) single lens of hexagonal aperture, (b) single lens of circular aperture, (c) circular aperture lens with the edge-shaped plate.

function, $w=25$, $n=20$-40) are 18-15% and 15.5-14%, respectively; this means that energy loss of the plate is almost the same as that of the soft aperture. The energy loss at the edge-shaped plate is mainly due to the deflection of the beam toward the outside of the target. This edge shape was fabricated by the polishing process. The beam pattern of the circular aperture with an edge-shaped plate is shown in Fig. 2(c), where, an almost flat-top profile is seen.

Although the geometrical energy loss of the circular-aperture lens array is approximately 12%, the final loss of the hexagonal aperture is the same if we irradiate a spherical target. The circular aperture has a large advantage because the edge-shaped plate can be used concurrently.

## 4. One-Dimensional Lens Array

We used a one-dimensional lens array to mitigate the influence of diffraction, and to control the intensity distribution of the beam on the target without defocusing. The one-dimensional lens array of 7 spherical lenses 40 m in focal length and 50 mm in diameter was tested with and without the 40 mm in diameter edge-shaped plate. The lens array was placed in front of the main focusing lens as shown in Fig. 3, and the edge-shaped plates were also placed in front of the lens array. One-dimensional intensity distributions of beam patterns without and with the edge-shaped plates are shown in Figs. 4(a) and (b), respectively. These intensity distributions were asymmetric because they included the intensity modulation of the source beam used in this measurement. The interference fringe between the individual beamlets is observed in the beam pattern. However, this interference fringe in the figure is incompletely shown as small-scale intensity modulation due to the lack of resolution of the measurement system because the focus of the measurement was placed on the observation of the reduction of diffraction fringes. In Fig. 4(a), the intensity distribution is modulated due to the Fresnel diffraction ring. In this case, the diffraction rings were incompletely overlapped due to the alignment error of each element lens. As shown in Fig. 4(b), the beam profile with the edge-shaped plate does not include diffraction rings, and the intensity modulation has been improved significantly. In this experiment, the beam did not have a flat-top profile. This was due to the incompleteness of the surface profile of the available edge-shaped plates used in this measurement.[7]

## 5. Two-Dimensional Lens Array

The two-dimensional lens array was composed of 37 spherical lenses 40 m in focal length and 50 mm in diameter. The lens array was placed in front of the main focusing lens with a 400 mm aperture and 1 m focal length. Since a sufficient number of edge-shaped plates was not available at the time of experiment, no edge-shaped plate was used in this measurement. The error in the position of the element lens was less than 0.5 mm, and the focal length error was within 5%. The beam pattern of lens arrays includes fine interference fringes of less than 10 $\mu$m pitch on the target. This fringe separation is fine enough for uniform illumination because thermal smoothing is effective in the target plasma.

In a high-power laser system, an amplified laser beam is modulated by the optical aberration of optical elements and the gain distribution in the laser medium. Therefore, optics of beam smoothing should provide a uniform beam profile even if the aberration of the laser beam is large. We tested the two-dimensional lens array using the He-Ne laser beam of a large-diameter interferometer with and without an additional phase aberrator; a schematic illustration is shown in Fig. 5. The aberrator was made of a soda glass plate which had an aberration on the order of a few

$\lambda$. The transmission interferogram of the aberrator is shown in Fig. 6. The beam pattern of the He-Ne laser beam focused to 1 mm in diameter without and with the aberrator are shown in Figs. 7(a) and (b). The beam pattern is strongly modulated with the aberrator in Figs. 7(b). Figure 7(c) and (d) show the beam patterns of two-dimensional lens arrays without and with the aberrator, and no change is seen with the aberrator insertion.

A concentric-circle structure due to the diffraction fringe is still visible in Fig. 7(c). However, the edge-shaped plate or the soft aperture can be used to eliminate this fringe. The experimental results shown in Figs. 7(a)–(d) indicate the effectiveness of the MLA, and no fatal disadvantage, such as a Moire fringe or a beat wave of the interference fringes, was observed in the two-dimensional lens array with a circular aperture.

## 6. Conclusions

In the MLA irradiation scheme, the lowest mode of the intensity modulation on a spherical target is determined by the beamlet size. Beam diffraction from the edge of the element lens is suppressed by shaping the edge structure of the element lens or the edge-shaped plate. The one-dimensional lens array has been tested with and without the edge-shaped plates. The experimental result demonstrated the advantage of using the edge-shaped plate in the multi

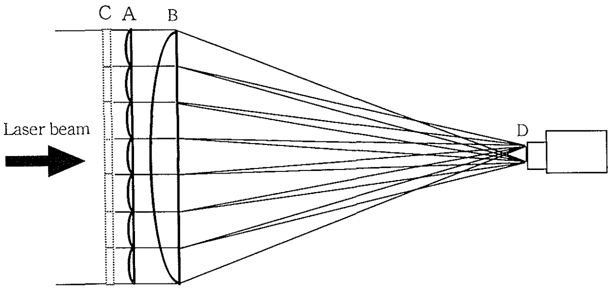


Fig. 3. Experimental setup of one-dimensional lens array with edge shaped plates. A, multi lens array; B, Main focus lens; C, edge shaped plates; D, CCD camera with imaging lens.

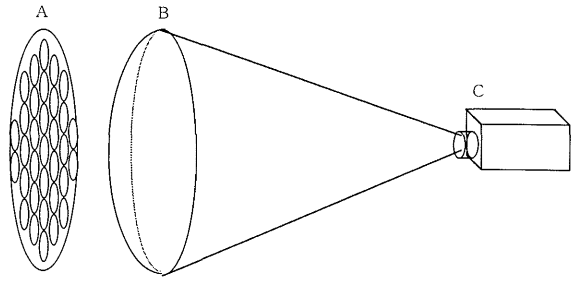


Fig. 5. Schematic illustration of the beam pattern measurement system for two-dimensional lens array. A, two-dimensional multi lens array; B, Aspherical focusing lens; C, TV camera with Image processing unit.

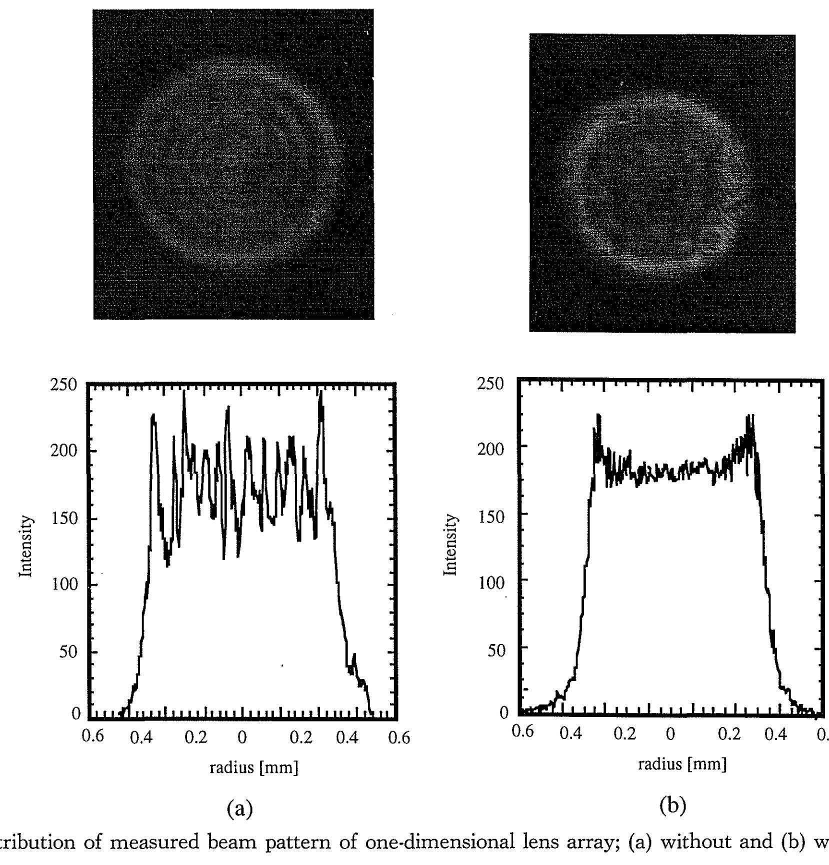


Fig. 4. Intensity distribution of measured beam pattern of one-dimensional lens array; (a) without and (b) with the edge-shaped plates.

lens array for obtaining a uniform beam profile (in this case, a flat top) on a small target (less than 1 mm in diameter). One advantage of our method is the elimination of defocusing of the target, which was requisite in the previous MLA approach. A two-dimensional multi lens array composed of 37 spherical lenses 40 m in focal length and with a circular aperture of 50 mm in diameter was fabricated and tested. Intensity modulation of the incident beam is mitigated, and an approximately flat-top intensity distribution is obtained using a coherent laser with a MLA. The interference fringe separation of the MLA is about 10 $\mu$m on the target. This experimental result demonstrates the effectiveness of the MLA scheme in controlling the beam profile in the ICF experiment. Extended investigations on the angular dependence of the absorption coefficient in the target plasma are required.

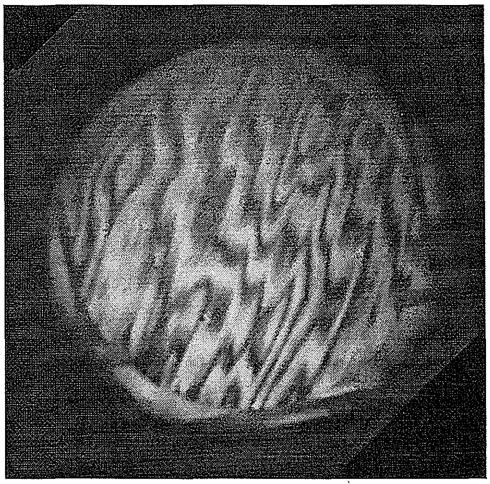

Fig. 6. Transmission interferogram of the aberrator.

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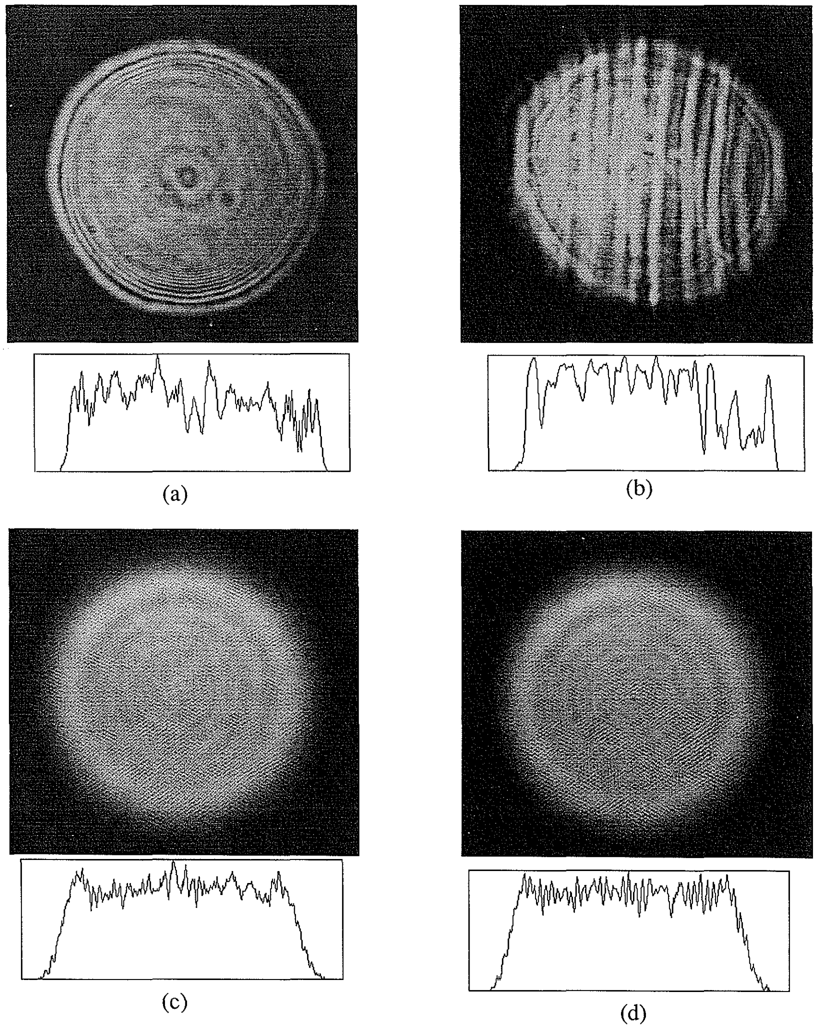

(a) (b) (c) (d)

Fig. 7. The beam pattern of the He-Ne laser beam focused to 1 mm in diameter: (a) Normal beam, (b) Normal beam+aberrator, (c) Normal beam with two-dimensional MLA, (d) Normal beam+aberrator with two-dimensional MLA.

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